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Failure Mechanisms for III-nitride HEMT devices

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Abstract: Advanced electron microscopy methods, in particular high-resolution imaging, nanoscale elemental mapping and off-axis electron holography, were used to investigate aspects of III-nitride HEMT materials and devices. Energy-filtered imaging of unstressed and stressed Ni/Au-gated AlGaN/GaN HEMTs indicated that structural defects present in the latter consisted of a nickel-aluminum-gallium oxide. Observations of ultrathin-barrier AlN/GaN HEMTs grown on freestanding GaN substrates demonstrated that no threading dislocations had been initiated by the AlN nucleation layer. Detailed electron holography examinations of specially prepared stressed AlGaN/GaN HEMT devices were initiated with the goal of providing additional information about the effects of very strong electrostatic fields implicated in device degradation. Finally, sample preparation methods involving wedge-polishing and focused-ion-beam milling were also refined.

Introduction: High electron mobility transistors (HEMTs) that are based on AlGaN/GaN heterostructures, are of much interest for high-voltage, high-frequency applications. However, extended operation and accelerated lifetime testing of such devices under high temperature conditions often lead to premature and unexplained failure, which is not necessarily related to the degradation mechanisms that prevail during operation of actual devices. Observations of highly stressed HEMTs using transmission electron microscopy (TEM) have indicated that regions close to and underneath the gate contact were physically modified during operation. However, relatively little information about any associated chemical or structural changes has been reported, and the underlying physical cause(s) of these defects remain to be unambiguously

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14. ABSTRACT
The primary objective of this project is to develop greater predictive knowledge and understanding of nitride HEMT devices and lifetimes. This goal will be accomplished by providing detailed information and insights about failure mechanisms, structural degradation and device lifetimes using advanced electron microscopy techniques.

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identified. Systematic studies of stressed and failed devices that correlate microstructural and chemical changes with device properties are necessary in order to fully elucidate the reasons for device failure and the broader ramifications for long-term device reliability. The primary objective of this research program was to contribute towards a better understanding of device failure mechanisms.

Experimental details

***Techniques**:* The transmission electron microscope (TEM) is a powerful instrument widely used for advanced materials characterization, with a range of imaging and analytical techniques that provide complementary information about defect microstructure and local chemistry. For example, high-resolution electron microscopy enables direct imaging of atomic arrangements at defects and interfaces. Nanospectroscopy uses a focused nanoprobe that can be scanned across the specimen to determine compositional profiles with spatial resolution approaching ~0.1nm and chemical sensitivities of ~1% or better using either electron-energy-loss spectroscopy (EELS) or energy-dispersive X-ray spectroscopy (EDXS). The technique of energy-filtered imaging uses electrons which have lost characteristic element-specific amounts of energy to provide two-dimensional elemental mapping with sub-nanometer resolution, thus enabling local changes in chemical composition to be determined at the nanoscale. Finally, off-axis electron holography is an interferometric TEM technique, made possible using a highly coherent field-emission electron source, that provides access to the relative phase change of the electron wave transmitted by the sample. Quantification of the phase by electron holography in turn permits two-dimensional visualization and measurement of internal electrostatic fields with nanometer-scale resolution.

***Equipment**:* The following instruments were extensively used in this project: i) *Philips CM200-FEG* 200-kV high-resolution and microanalytical TEM with information limit to 0.14nm, and focused probe size down to ~ 0.5nm. This instrument is equipped for energy-dispersive X-ray spectroscopy (EDXS) as well as parallel electron-energy-loss spectrometer (EELS) and imaging filter allowing chemical analysis and elemental mapping. It also has a high-magnification Lorentz lens with an interpretable resolution of 2.0 nm (1.4 nm information limit), an electrostatic biprism, and a 1024x1024 CCD camera. These latter facilities enable quantitative off-axis electron holography studies of electrostatic (and magnetic) fields down to the nanometer scale. ii) *JEM-2010 FEG-TEM* with high-resolution and microanalytical capabilities, including focused probe smaller than 0.2nm, "Z-contrast" or annular-dark-field (ADF) imaging, EDXS and EELS. iii) *JEM-4000EX* 400-kV high-resolution electron microscope with point resolution of better than 0.17nm. iv) *FEI Nova 200* dual-beam FIB/SEM, equipped with OmniProbe liftout and Short-Cut systems, which provides site-specific, ion-milling capability with simultaneous sample observation using ultrahigh-resolution scanning electron microscopy.

Results and Discussion: The longer-term research objectives of this program were directed primarily towards as-processed HEMT devices, and comparisons with device structures after they had been subjected to extended periods of operation and after total stress failure and/or device breakdown. Observations concentrated mainly on AlGaN/AlN/GaN and related heterostructures and devices, in close collaboration with groups from elsewhere, including Prof. Fan Ren and colleagues (U. Florida), Dr. David Storm (Naval Research Laboratory), and Dr. Xiang Gao of IQE.

a) Structural defect formation and compositional analysis in stressed Ni/Au-gated AlGaN/GaN HEMTs (work in collaboration with M. Holzworth, K.S. Jones and colleagues at U. Florida)

In this study, AlGaN/GaN HEMTs grown on a semi-insulating 6H-SiC substrate were

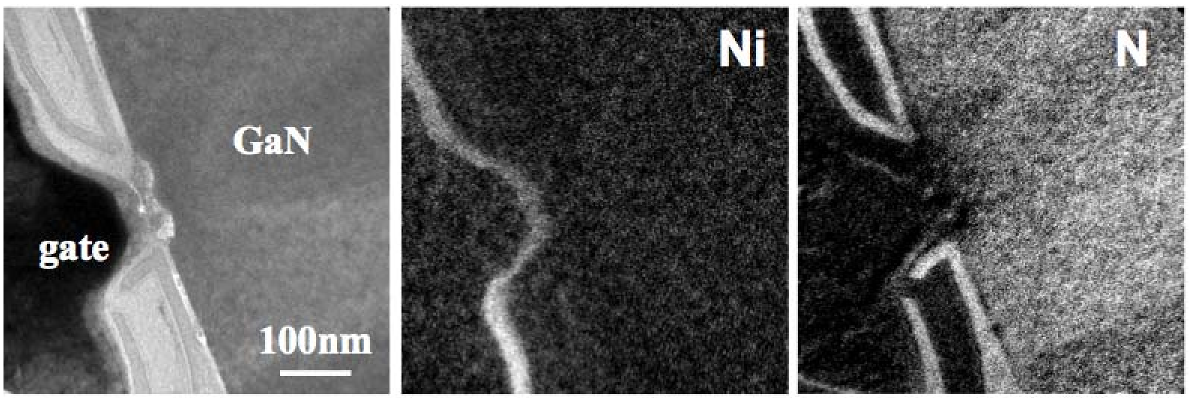

Fig. 1. EFTEM mapping of AlGaN/GaN HEMT showing region close to gate contact.

stressed under high-reverse bias conditions causing the formation of structural defects that were attributed to a chemical reaction between the Ni-layer of the gate contact and the underlying AlGaN epilayer. Chemical maps and line scans across the defective regions were obtained using Energy-Dispersive X-ray spectroscopy (EDXS), Electron Energy Loss Spectroscopy (EELS), and Energy-Filtered TEM, as shown by the representative example in Fig. 1. Comparison of the chemical profiles for unstressed and stressed devices indicated that the defects in the latter consisted of a nickel-aluminum-gallium oxide.

b) Characterization of ultrathin-barrier AlN/GaN HEMTs on freestanding GaN substrates (work in collaboration with D.F. Storm and colleagues at NRL)

This study involved AlGaN/GaN and ultrathin-barrier AlN/GaN high electron mobility transistor structures which were grown by rf-plasma MBE on freestanding, Ga-polar, hydride

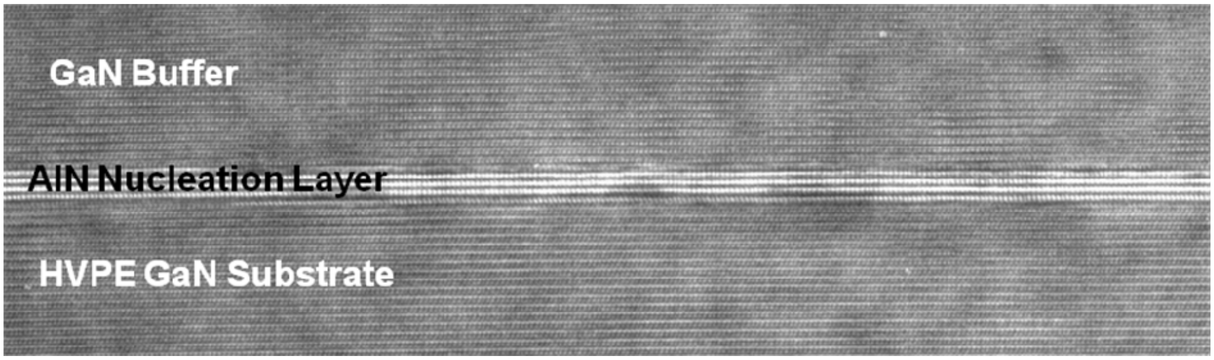

Fig. 2. High-resolution electron micrograph of GaN/AlN/(HVPE) GaN interfacial region showing continuity of AlN layer and sharp GaN/AlN and AlN/GaN interfaces.

vapor phase epitaxy (HVPE) GaN substrates using a thin (~1.5 nm) AlN nucleation layer. The AlN layer thicknesses and interfaces were evaluated by transmission electron microscopy (TEM), as shown by the example in Fig. 2. Cross-sectional TEM imaging indicated that high structural quality was achieved through the AlN nucleation and GaN layers near the substrate. In particular, no threading dislocations were found to have been generated because of the AlN layer over lateral distances of more than 5 microns.

c) Potential profile mapping across stressed AlGaN/GaN HEMT device (work in collaboration with F. Ren and colleagues at U. Florida)

It is well known that strong spontaneous polarization fields are present in nitride HEMT devices as a result of the wurtzite crystal structure, and these are in addition to the piezoelectric fields that are caused by pseudomorphic misfit strain across the hetero-interfaces. These very strong fields, which can reach several MV/cm depending on the specific heterostructure and individual layer thicknesses, are likely to play a dominant role in determining the prevalent device failure mechanism(s). The presence of these fields also leads to the accumulation of sheet charge, usually referred to as a two-dimensional electron gas (2DEG), close to the AlGaN/GaN heterointerface. The presence of the 2DEG is advantageous for HEMT device applications because of the ready supply of charge carriers without any need for introducing dopant profiles. Off-axis electron holography in the TEM offers a direct method for quantifying both the potential profiles and the 2DEG present in actual device structures.

Electron holography represents a unique and powerful approach for making quantitative measurements of electrostatic potential profiles within real devices with a spatial resolution approaching the nanometer scale. Since very strong piezoelectric fields are believed to be a major factor contributing to device failure, this research program paid close attention to electron holography studies of stressed devices. Figure 3 shows an example of potential profile mapping for a stressed AlGaN/GaN HEMT.

During much of the period covered by this report, electron holography studies with the CM-200 FEG-TEM were significantly compromised by an almost never-ending succession of

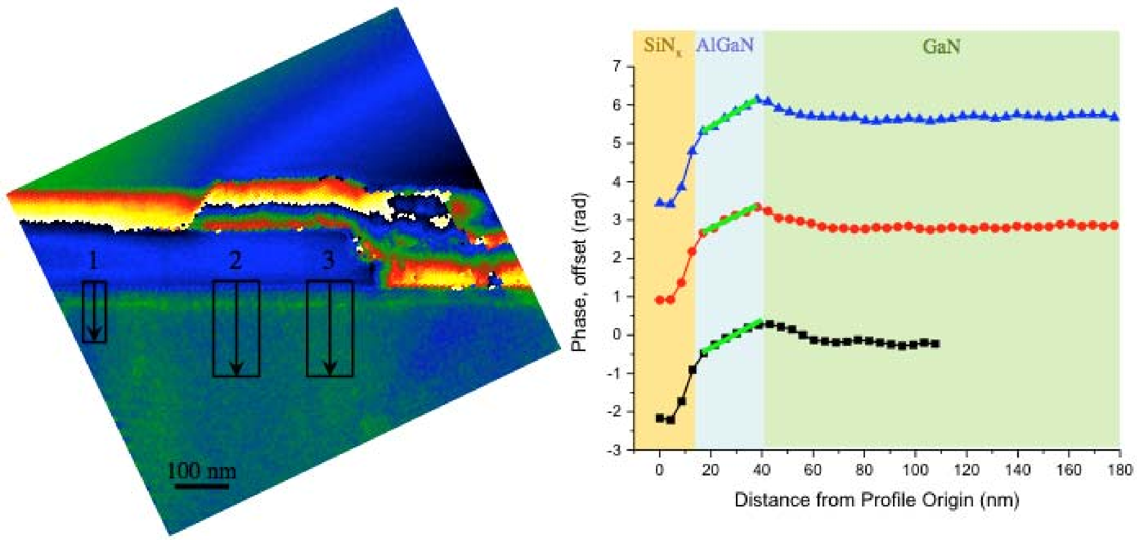

Fig. 3. (L) Reconstructed phase image of AlGaN/GaN HEMT; (R) Phase profiles from indicated regions. Slope in phase corresponds to internal electric fields across the AlGaN layer in the range of 0.6-0.75 MV/cm.

mechanical failures and electrical instabilities so that the scope was only available for use on an infrequent basis. The FEI Company eventually replaced the high-voltage accelerator, and installed a new electron gun, and the scope was finally restored to working better than ever before except for a small instability in the Lorentz lens that limited spatial resolution to ~5nm in the wide-field-of-view operating mode. Measurements of interference fringe contrast were higher than ever measured previously with this instrument.

Further systematic comparisons between as-processed and stressed devices are still needed in order to develop better insights into the predominant failure mechanism(s), in particular to correlate device operating characteristics with changes observed in device morphology, local chemistry, and electrostatic fields. *In situ* biasing experiments proved to be difficult to implement during concurrent electron holography observations because of the demanding specimen-microscope geometry. Methods for sample biasing within the electron microscope will require further attention in order to become more robust and reliable for future holography studies

Other activities: Student Michael Johnson gave invited talks at the 2011 Microelectronics Reliability & Qualification Workshop (MRQW) held in Los Angeles in December 2011, and at the Microscopy and Microanalysis 2012 meeting held in Phoenix in July 2012. Johnson also defended his Ph.D. dissertation in November 2012 and graduated in December 2012. Two new physics Ph.D. students, namely Thomas McConkie and Allison Boley, replaced Johnson and they starting working on different aspects of this research program. McConkie's primary assignment was to study defects and degradation mechanisms, while Boley concentrated mostly on continuing with the electron holography studies.

List of Publications, Talks and Significant Collaborations

i) Publications

Johnson, M.R., Cullen, D.A., Liu, L., Kang T.S., Ren, F., Chang, C.-Y., Pearton, S.J., Jang, S., Johnson, W.J., and Smith, D.J. (2012) Transmission electron microscopy characterization of electrically stressed AlGaN/GaN high electron mobility transistor devices, J. Vac. Sci. Technol. B 30, 062204.

Wang, X., Lo, C.-F., Liu, L., Ceurvo, C.V., Ren, F., Pearton, S.J., Gila, B., Johnson, M.R., Zhou, L., Smith, D.J., Kim, J., Laboutin, O., Cao, Y., and Johnson, J.W. (2012) 193-nm excimer laser lift-off for AlGaN/GaN high mobility transistors, J. Vac. Sci. Technol. B 30, 051209.

(invited) Johnson, M.R., Smith, D.J., Zhou, L., McCartney, M.R., and Cullen, D.A. (2012) Quantifying polarization fields and sheet charge in III-nitride HEMT devices using off-axis electron holography, Microscopy and Microanalysis 17, Supp. 2 (Proc. Microscopy and Microanalysis 2012, Phoenix) pp. 1832-1833CD.

A. Boley, H. Sun, M.R. McCartney, D.J. Smith, and T.D. Moustakas, Characterization of AlGaN-based GRINSCH using TEM and Electron Holography, Microscopy and Microanalysis 17, Supp. 2 (Proc. Microscopy and Microanalysis 2012, Phoenix) pp. 1816-1817CD.

D.F. Storm, D.A. Deen, D.S. Katzer, D.J. Meyer, S.C. Binari, T. Gougousi, T. Paskova, E.A. Preble, K.R. Evans, and D.J. Smith, Ultrathin-barrier AlN/GaN heterostructures grown by rf plasma-assisted molecular beam epitaxy on freestanding GaN substrates, J. Cryst. Growth 380, 14-17 (2013).

ii) Conference presentations

(Invited) M.R. Johnson, L. Zhou, and D.J. Smith, "TEM studies of nitride HEMT devices and materials", at *Microelectronics Reliability and Qualification Workshop,* Los Angeles, CA, December 2011.

M. R. Holzworth, N. G. Rudawski, P. G. Whiting, C. Y. Chang, E. A. Douglas, S. J. Pearton, D. J. Smith, L. Liu, T. S. Kang, F. Ren, E. Patrick, M. E. Law, L. Zhou, M. R. Johnson, and K. S. Jones, "Structural defect formation in Ni-Gate AlGaN/GaN HEMTs", at *Materials Research Society Spring Meeting*, San Francisco, CA, April, 2012.

D.F. Storm, D.A. Deen, D.J. Meyer, D.S. Katzer, S.C. Binari, T. Paskova, E.A. Preble, K.R. Evans, L. Zhou, and D.J. Smith, "MBE-grown AlGaN/GaN and ultrathin AlN/GaN HEMT structures on freestanding GaN substrates", at *NAMBE 2012*, Stone Mountain Park, GA, October, 2012.

iii) significant collaborations

a) Stressed Ni/Au-gated AlGaN/GaN HEMTs - in collaboration with M. Holzworth, K.S. Jones and colleagues at U. Florida.

b) Ultrathin-barrier AlN/GaN HEMTs on freestanding GaN substrates - in collaboration with D.F. Storm and colleagues at NRL.
c) Potential profile mapping across stressed AlGaN/GaN HEMT device - in collaboration with F. Ren and colleagues at U. Florida.